

# Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)

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## PROJECT SUMMARY

### Overview

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, in June 2004, an air-sea flux buoy site was launched at 144.5°E, 32.3°N in the Kuroshio Extension recirculation gyre. The mooring, referred to as the Kuroshio Extension Observatory (KEO), carries a suite of sensors to monitor carbon dioxide uptake; air-sea heat, moisture and momentum fluxes; temperature and salinity to 500 m, and near-surface currents. The Kuroshio Extension (KE) is the North Pacific's western boundary current after separating from the coast near 35°N. The KE jet carries approximately 140 million cubic meters per second (140 Sv) of warm water eastward into the North Pacific. About a third of this is forced by the basin-scale winds and associated with the wind driven Sverdrup transport and the other 90 Sv is due to a tight recirculation gyre whose size varies on seasonal-decadal time scales.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby excess heat input at the top of the atmosphere in the tropics is carried poleward by a combination of the oceanic and atmospheric circulations (e.g., Trenberth and Caron 2001). In the subtropical North Pacific, a significant fraction of this heat is transported poleward by the Kuroshio. As cold dry air of continental origin comes in contact with the warm KE water, heat and moisture are extracted from the surface (Fig. 1), resulting in deep convection and rainfall. The KE is co-located with the Pacific storm track and heat released to the atmosphere is then carried further poleward through the action of storms.

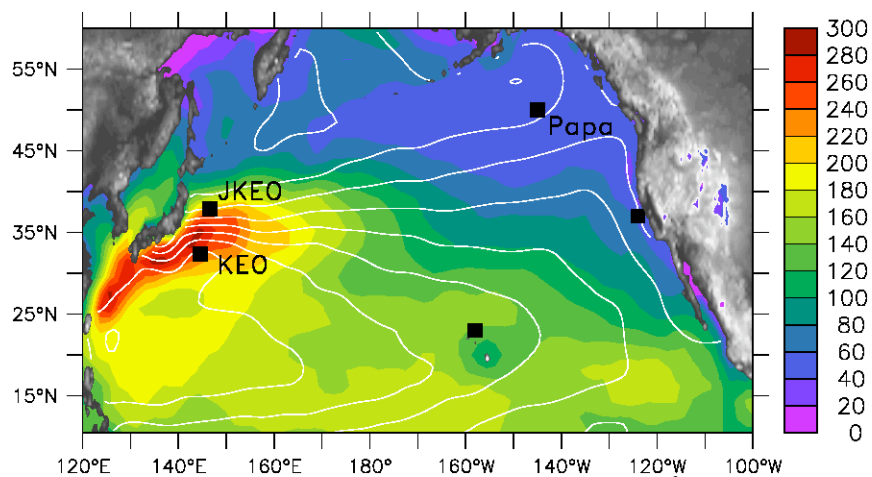


Fig 1. Climatological wintertime (January-March) latent heat flux (color shade in  $Wm^{-2}$ ) and sea level height (white contours) for the North Pacific. Squares indicate OceanSITES time series reference sites.

The ocean has particularly strong influence on the atmosphere in the KE region because the

heat content is extraordinarily large on the southern side of the KE jet. Indeed, wintertime cooling erodes the seasonal stratification, producing a thick (up to 400 m thick) isothermal  $\sim 17^{\circ}\text{C}$  surface layer, termed *Subtropical Mode Water* (STMW). The STMW acts as a reservoir of heat. After it is isolated beneath the seasonal thermocline, it retains its water mass characteristics, reemerging the following winter to once again interact with the atmosphere. Through this “re-emergence mechanism”, mode water formed in a given winter is expected to affect SST in the subsequent fall and winter. Mode water formation is also associated with the sequestering of carbon. In addition to having some of the largest air-sea heat fluxes found in the entire basin, the region also characterized by intense carbon dioxide uptake. Without uptake of significant amounts of the  $\text{CO}_2$  released from human activity, climate change would be much more pronounced. The KE region thus plays a critical role in the global carbon cycle and climate system.

The KEO project is working closely with international research communities. The KEO site was within the study domain of the 2-year (June 2004 - June 2006) National Science Foundation-funded Kuroshio Extension System Study (KESS). KEO data are being combined with KESS data for a series of analyses on mode water formation, seasonal thermocline erosion, recirculation gyre strength, and air-sea interaction associated with summer typhoons and winter storms in the region. KEO data also serve the operational community and are being used as reference time series to assess numerical weather prediction analyses and reanalyses (e.g. Kubota et al. 2007).

With surface currents of 3 knots ( $\sim 150$  cm/s) or more, a typically rough sea state, and lying in the Jet Stream's storm track, the KE is an extremely difficult region to observe. Ships have been the traditional platform for observing air-sea interaction in western boundary currents. However, research cruises typically last no more than a month or two, and measurements from research ships and vessels of opportunity are biased towards good weather. With the success of the KEO time series reference site, PMEL has been approached by several other potential partners. In particular, the KEO project is working closely with scientists from the Japan Agency for Marine Earth Science and Technology (JAMSTEC) and in February 2007, JAMSTEC Institute of Observational Research for Global Change (IORGC) in partnership with NOAA PMEL successfully deployed a NOAA-designed KEO mooring (JAMSTEC-KEO or “JKEO”) north of the Kuroshio Extension jet. In addition, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington, in June 2007 PMEL deployed a KEO-type air-sea flux mooring at the Ocean Weather Station Papa in the Northeast Pacific. The Papa and JKEO offshoots of KEO represent an expansion of the OceanSITES array. Meteorological data from all three sites are available in near-real time through the Global Telecommunication System (GTS). Near-realtime surface and subsurface data as well as delay mode data are available in ascii and the standard OceanSITES netcdf formats through website browsers and anonymous ftp sites. For more details on the KEO project and to access the realtime and delay mode data, see the KEO project website: <http://www.pmel.noaa.gov/keo/>. For JKEO, see: <http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/> and for Station Papa see: <http://www.pmel.noaa.gov/stnP/>.

## **FY2007 ACCOMPLISHMENTS**

The KEO project has 3 broad deliverables, each described below. The Carbon component of KEO is described separately in the progress report for Sabine's “High-Resolution Ocean and Atmosphere  $\text{pCO}_2$  Time Series Measurements” project.

**Deliverable 1: Calibrated surface meteorological and subsurface temperature, salinity and currents at the KEO site in the Kuroshio Extension recirculation gyre at 32.3N, 144.5E.**

Operation of the KEO mooring requires refreshing the system at least once a year, pre- and post-calibrating all sensors, processing realtime data and making it available in near-realtime through the KEO website, processing delay-mode high resolution data and making it available with 6 months through the KEO website.

The KEO mooring was redeployed using charter funds for two sea-days on the R/V Kaiyo in September 2007. As shown in Fig. 2, the KEO-2007 mooring has a larger 2.5 m discus hull than the original retrofit TAO buoy. The new hull will make the buoy more robust to the drag caused by the strong full-water column currents. In addition, the larger hull will enable the buoy to carry a larger payload, for example, a wave sensor package. The upgrade also included a barometric pressure sensor and duplicate meteorological sensors on an independent data logger and telemetry system (Fig. 2). Given the high number of typhoons in this region, this redundancy is prudent. Other changes to the KEO-2007 design included reduction in the overall number of subsurface modules.

Select time series are shown in Fig. 3. The full suite of KEO meteorological measurements include: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. Daily-averages of all met data are telemetered in near-realtime. Surface and subsurface measurements include sea surface temperature and salinity at 1 m (both of which are telemetered), subsurface temperature at 28 (20 on KEO-2007) depths down to 525m (12 of which are telemetered), subsurface salinity at 15 (11 on KEO-2007) depths down to 525m (5 [6 on KEO-2006] of which are telemetered), and pressure at 7 (5 on KEO-2007) depths (3 of which are telemetered). Thus upper ocean temperature has approximately 25 m depth resolution, subsurface salinity has ~50-75 m resolution, and subsurface pressure (to remap the slackline depths) has 75 m resolution. This resolution is necessary to monitor the mode water formation when the mixed layer can be more than 400 m deep. Three current meters were also attached at 5 m, 15m, and 35 m (all of which are telemetered) to monitor the near surface currents

During the 2006 typhoon season, KEO-2006 survived three class 5 typhoons. The only damage was the loss of the relative humidity sensor during the passage of third typhoon SOULIK on October 17 2006. Although we were very pleased by the minimal damage, because the KEO-2006 deploy did not have duplicate meteorological sensors, the loss of the critical relative humidity sensor meant that the air-sea heat fluxes could not be computed. Thus arrangements were made for a repair. We are very grateful to JAMSTEC, the Fisheries Agency of Japan, and the R/V Shoyomaru for their assistance in repairing this sensor in January 2007, and the OAR Office of International Activities for their help in arranging the repair. The KEO data provide an unparalleled in situ data set for typhoon (hurricane) studies.

On April 17, 2007, the buoy broke away from its mooring line and began drifting eastward in the fast-moving Kuroshio Extension. Because the buoy position is monitored on a daily basis, the project was immediately alerted of the failure and therefore able to make arrangements for a rescue. Within several weeks, the R/V Melville was able to recover the KEO buoy and its surface instrumentation. Since the high-resolution meteorological data are stored in the surface electronics “tube”, the recovery included not only valuable equipment, but also valuable data. Investigation of the recovered hardware and data revealed very strong evidence that the buoy had been picked up out of the water and damaged, likely by a fishing vessel. The KEO project is extremely grateful to the chief scientist (Dr. Craig Lee), the science party, and the captain and crew of the R/V Melville for the rescue.

Data returns are reported in Table 1 for the full 365 days of FY07 as well as for the 202 days total that a mooring was on site; this includes 198 days in the water before the cable parted (4/17/2007) and four days of the KEO-2007 real-time data in FY07. KEO2007 was deployed on 9/26/2007. Prior to the 9/26/2007 redeployment date, data return is based upon all sensors mounted on the mooring. FY07 data returns are noticeably worse than FY06 numbers due to the break and the loss of all instruments below the bridle. Since there are many subsurface temperature and salinity modules that do not report in real-time, these numbers are significantly skewed by the loss of the subsurface instruments. In addition, several sensors (current meters in particular) had telemetry problems. We are investigating other current meter manufacturers. As with previous years, the meteorological sensors had a very good data return when the mooring was in the water.

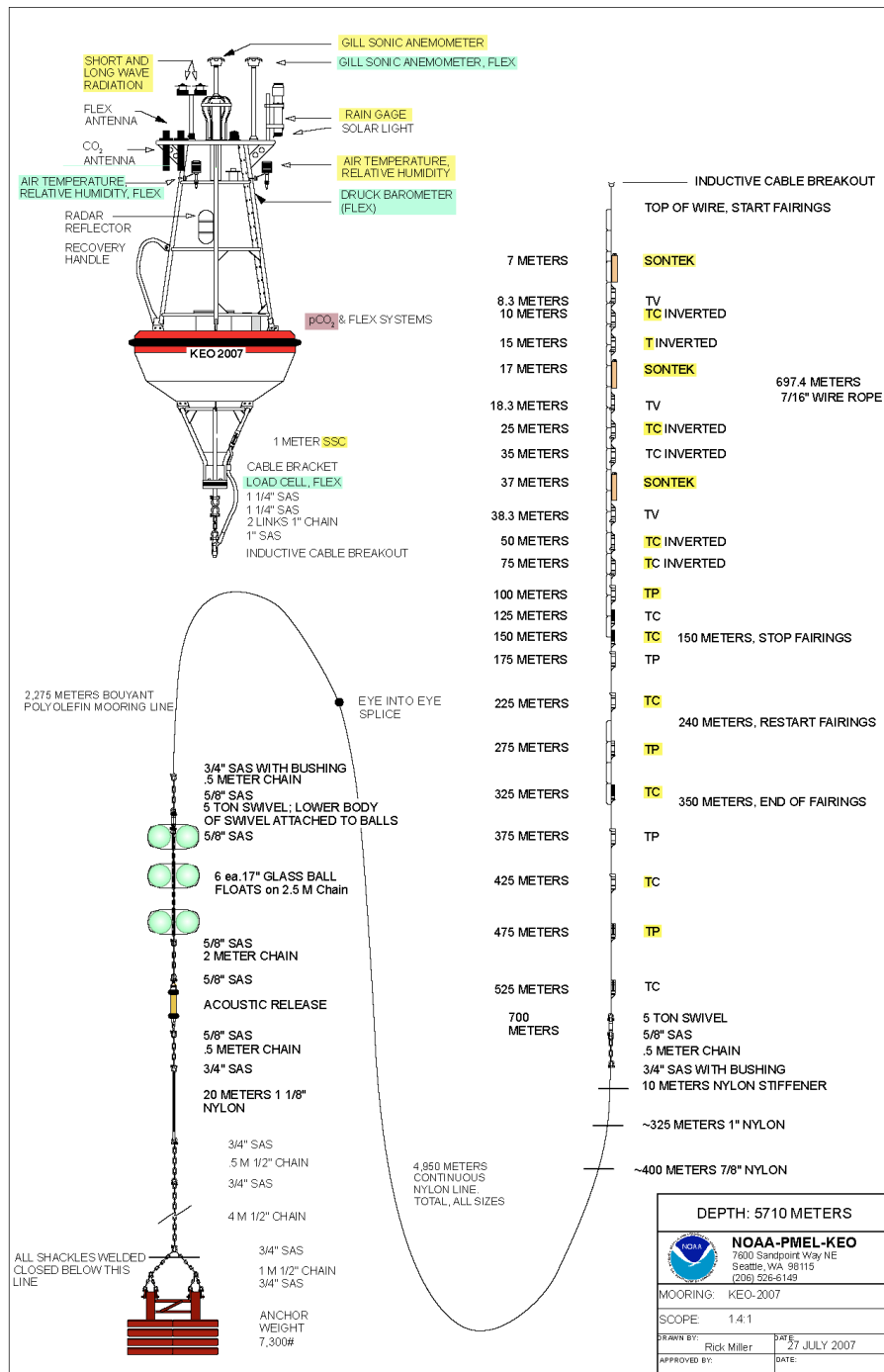


Fig. 2. KEO diagram. Telemetered measurements from three independent systems are highlighted in yellow(ATLAS); green (FLEX) and pink (pCO<sub>2</sub>).

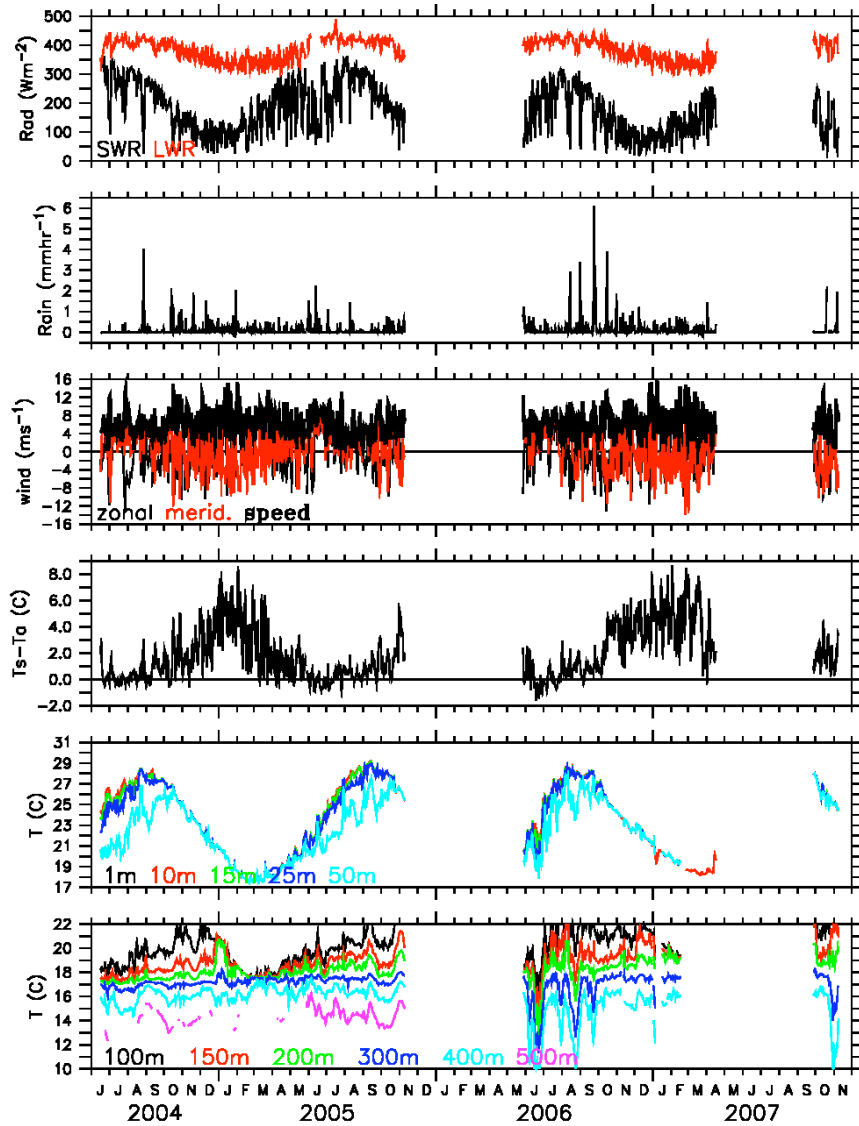


Fig. 3. Select KEO daily-averaged data through November 1 2007.

	FY07 Data Returns	
	full year	while on site
Meteorological variables	51%	93%
Upper ocean temperature	16%	29%
Upper ocean salinity	16%	28%
Near surface currents	10%	17%

Table 1. KEO data return for FY07 based upon daily-averaged delay-mode data and telemetered daily-averaged data after Sep 30, 2007.

The PMEL KEO group has also deployed two other KEO-type flux moorings with pCO<sub>2</sub> systems during FY07: At the JKEO site (38N, 146.5E) north of the KE jet mooring, through a partnership with JAMSTEC; and at station Papa (50N, 145W) in the Northeast Pacific, through a partnership with the University of Washington. The JKEO mooring, deployed in February 2007, is funded by JAMSTEC and operated by PMEL. Its sensor suite is similar to KEO-2006, but with fewer subsurface sensors. In February 2008, the NOAA-designed JKEO mooring is scheduled to be recovered and a JAMSTEC-designed K-TRITON mooring will be deployed that will be operated by JAMSTEC.

The station Papa mooring, deployed in June 2007, is funded through a subcontract on a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington. Like KEO and JKEO, the station Papa mooring monitors air-sea heat, moisture, momentum and carbon dioxide fluxes, and subsurface temperature, salinity, and currents. In addition it carries a second wind sensor, a barometric pressure sensor, a pH sensor, and two systems which measure O<sub>2</sub> and gas tension, from which the biological CO<sub>2</sub> pump can be inferred. With this suite of sensors, the station Papa mooring can be considered the first Ocean Acidification deep ocean mooring. Longterm funding for the Station Papa air-sea flux mooring still needs to be secured to continue the Papa mooring past the planned final recovery in August 2009.

**Deliverable 2: Access to KEO data and metadata in a format and through linked webpages to encourage broad use of data.**

KEO, JKEO and station Papa data are all in compliance with the OceanSITES data standard. Daily-averages of nearly all data (surface and subsurface) are telemetered to PMEL and made available in near-realtime from:

For KEO: <http://www.pmel.noaa.gov/keo/data.html>

For JKEO: <http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo>

For Station Papa: <http://www.pmel.noaa.gov/stnP/data.html>

High-resolution surface and subsurface data continue to be made publicly available through the KEO website within 6-months of recovery. To date, there is no user registry and so we have no way of monitoring the number of data downloads.

Prior to FY07, the KEO data had been withheld from the Global Telecommunications System (GTS) so that they can be used as an independent validation in comparisons with satellite and numerical weather prediction (NWP) fields. With the deployment of a second buoy in the region (JKEO), this decision was reviewed and it was decided that meteorological data from all three sites should be made available through the GTS. This way operational meteorological centers can use all available data in operational weather forecasts. The KEO project strongly believes however that the reference site data should be withheld from reanalysis products so that the products will remain independent of the time series reference site data used to assess them. Each time series reference station has a unique World Meteorological Organization (WMO) identifying number containing the digits “84” for this purpose.

Following the best practices for process studies advocated by the U.S. CLIVAR Process Study and Model Improvement Panel, a consolidated KESS data set is being served through the centralized access point. Thus a duplicate KEO data set for the first two years is also available through the KESS homepage: <http://uskess.org/>.

All three sites (KEO, JKEO, and Station Papa) can be considered as contributions to the Global Earth Observation System of Systems (GEOSS) and a manuscript describing the strategy of

these moorings has been submitted to the IEEE Systems journal special issue for GEOSS (Cronin et al. 2007).

**Deliverable 3: Scientific analyses utilizing KEO data. (Scientific analyses are funded through research grants as described below.)**

KEO data are a critical component of various scientific studies in progress. In particular, FY07 represents the second year of a 3-year NOAA CLIVAR project titled “Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre”, with PIs Cronin and Dr. N. Bond (UW JISAO). In November 2006, both Cronin and Bond participated in the KESS workshop held at the University of Rhode Island. In addition, during FY07, the U.S. CLIVAR working group on Air-Sea Interactions in Western Boundary Current regions was initiated (<http://usclivar.org/Organization/wbc-wg.html>). Both Cronin and Bond are members of this working group and have participated in the monthly teleconferences and at the August 2007 Working Group meeting in Portland OR.

Two KEO analyses are currently in press. Bond and Cronin (2007) analyzed the regional weather and climate patterns associated with anomalously high and low fluxes at KEO. The analysis shows that during the cool season, prevailing winds at KEO are northwesterly and anomalous heat loss by the ocean is associated with increased northerly winds (cold air outbreaks). During summer, on the other hand, prevailing winds switch to be southerly and anomalous cooling tends to occur during enhanced southeasterly winds out of the deep tropics. When the analysis was extended to identify weather patterns associated with anomalous fluxes on seasonal time scales, a surprising result was found. The warm seasons with anomalous heat fluxes tend to have composite patterns similar to the episodic composites, but the cool seasons with anomalous heat fluxes have composite circulation patterns that are weak and little resemble their episodic event counterparts. It's not just a matter of having more or less cold-air outbreaks. Instead, these results suggest that on interannual timescales, the ocean may be playing an important role in determining wintertime heat flux anomalies.

The KEO data have also been used as a time series reference to assess Numerical Weather Prediction (NWP) forecast analyses and reanalyses, and other numerical and satellite products. In particular, Kubota et al. (2007) used the KEO data to assess the radiative and turbulent heat flux fields of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and NCEP/Department of Energy (DOE) reanalyses (referred to as NRA1 and NRA2) and found that:

- Overall, the NRA latent heat losses were too large relative to KEO. For NRA1, the latent heat bias was  $41 \text{ W/m}^2$ ; for NRA2, the bias was  $62 \text{ W/m}^2$  (there was a  $21 \text{ W/m}^2$  bias between the two products).
- Although the magnitude of the fluxes had significant biases, the NRA were able to capture many of the synoptic disturbances. The cross-correlation between the KEO latent heat flux and the co-incident NRA latent heat fluxes were greater than 0.9 for both NRA1 and NRA2.
- The bias in the NRA latent heat flux could be reduced significantly by using a more sophisticated bulk algorithm for its heat flux calculations.
- Of all the state variables (SST, humidity, air temperature, wind speed), humidity contributed the largest source of error to the NRA flux. During summer when prevailing winds are from the south (of maritime origin), the NRA humidity is too low, while during the winter when prevailing winds are from the north (of continental origin), the humidity

is too high. Although the prevailing wind systems are well reproduced, the air humidity does not seem to be properly modified by boundary layer effects.

- The NRA SST had significant errors in comparison to KEO measurements. The RMS error in latent heat flux was significantly reduced when the NRA SST was replaced with the Microwave Optimum Interpolation (MWOI) SST, indicating that both reanalyses could be improved by assimilating better SST data.

The KEO group is hoping to work more closely with scientists at NCEP to evaluate the operational products and to improve our understanding of air-sea fluxes leading to better predictions of weather and climate variations.

## **FY07 Bibliography**

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## **7. List of Acronyms**

CLIVAR	Climate Variability and Predictability
DOE	Department of Energy
FLEX	Flexible Low-powered Electronics for ocean eXperiments
GTS	Global Telecommunications System
IORGC	Institute of Observational Research for Global Change
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JKEO	JAMSTEC-Kuroshio Extension Observatory
KE	Kuroshio Extension
KEO	Kuroshio Extension Observatory
KESS	Kuroshio Extension System Study
K-TRITON	Kuroshio-TRIangle Trans-Ocean buoy Network
MWOI	MicroWave Optimum Interpolation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NRA1	NCEP/NCAR Reanalysis
NRA2	NCEP/DOE Reanalysis
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OceanSITES	Ocean Sustained Interdisciplinary Time series Environmental Observatory
PMEL	Pacific Marine Environmental Laboratory
RMS	Root-Mean-Square
SST	Sea Surface Temperature
STMW	Subtropical Mode Water
TAO	Tropical Atmosphere and Ocean
UW	University of Washington
WMO	World Meteorological Organization